Interim Report 1

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Background and Introduction

In recent years, the detection of binary neutron star merger events has presented an opportunity to learn about the exotic physical properties that are irreplicable in laboratory experiments. These merger events, in which a pair of orbiting neutron stars (NS) collide, are detectable on Earth through the aLIGO gravitational wave detectors.

There are, however, some challenges to detecting binary neutron star mergers; the signals from the gravitational radiation are typically separated into two parts: a *pre* and *post-merger* signal. The pre-merger signal is detectable with well-researched information on the responsible bodies, while the post-merger signal carries the balance of the information necessary to learn about the coalesced object. In the example of GW170817, the first such event to be detected, the pre-merger information was used to measure the radii of the coalescing neutron stars and to place meaningful constraints on both their equations of state (EoS) and their tidal parameters. But no post-merger signal was detected, presumably hidden within detector noise at frequencies beyond the optimized band of the detectors.

Research has identified needed improvements to access post-merger data. For example, [1] proposes that this can be achieved through improving detector sensitivity in the kilohertz range by 2 to 3 times current capabilities through the use of quantum squeezing, which by the Heisenberg uncertainty principle, allows us to better determine a variable at the cost of another. Observing run four, (abbreviated O4) has started and includes some techniques to improve sensitivities (including light squeezing). New signals from O4 could contain post-merger frequencies, providing the ability to improve models and understanding of BNS merger events.

This sensitivity issue is shown in the figure below 1; where we can see the frequency of the signal growing beyond the range of the detectors as the bodies merge.

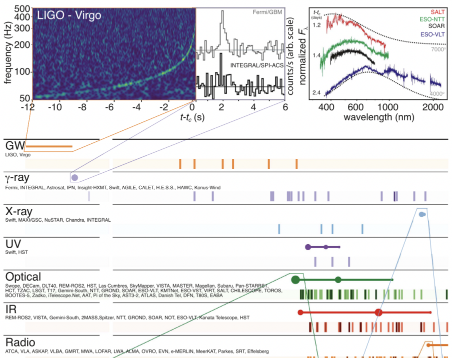

Figure 1: The multi-messenger signal from a BNS merger. Adapted from [2]

This Project

My project is to help resolve the still mysterious equations of state that structurally govern neutron stars. Better modeling of the evolution of binary neutron star coalescence will allow 1) better understanding of what the post-merger signal structures, making them easier to find, and 2) once found, allow us to further constrain NS EoS choices. The equation of state will distinctly present itself in themselves in GW wave phase as it determines the distribution of mass within the star and the deformability of NS matter. Originally my project was to develop analytical algorithms to determine the distinguishability of direct collapse mergers from those that leave stable, long-lived remnants to help inform the next generation of detectors about what to search for. However, this work has been done since my project proposal and is explored in [3] who found distinct signals depending on the final remnant, as shown in the figure below.

In Figure , a distinct fingerprint in the post-merger signal of a binary Neutron star merger is associated with both the remnant left behind and the speed with which it formed. This finding will prove significant in detecting and understanding postmerger signals of future events, but required a new direction for my project.

My current project now involves working on the simulations of BNS mergers, particularly the potential to improve their accuracy at a reasonable computational cost. The papers [4] and [**?**] both discuss the algorithms currently used in simulating merger events. Both papers discuss issues arising in the numerical evaluation of General relativity and Einstein's equations that govern such extreme spacetimes. Neutron stars, which actually have matter, are harder to evolve in simulation. Both [4]and [**?**] investigate alternatives using EOS's for numerical simulations with discontinuities only in higher-order derivatives and use piecewise functions clustered around the remaining discontinuities, to get more accurate simulations at a comparable computational cost. More accurate simulations like these will clearly provide better information on what future signals should look like. The next step is to investigate the impact of smaller

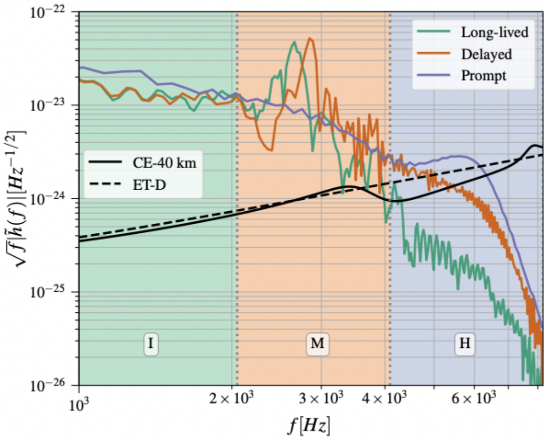

Figure 2: Typical signals for three binary neutron star mergers forming distinct remnants, a promptly collapsed Blackhole, a Short-Lived Neutron star eventually leaving a Blackhole, and a Long-Lived Neutron star.

computational cells in these simulations. Improving the resolution will require a larger number of cells to evolve the same simulation, but has the potential to further improve accuracy. The primary question is just how much more physical accuracy we can achieve through both varied computational methods and equation of state choice.

With the change in project direction, work to date has been mostly preparatory; familiarizing myself with the analysis methods of the LIGO collaboration, learning general methods of event detection and noise filtering, and creating programs of my own to numerically model stars. Most recently, I have used the SpECTRE program referenced in [4] to create merger simulations of head-on collisions between Binary Neutron stars. These head-on collisions begin with two stars at rest in falling to collide, in reality, we expect natural BNS to be orbiting each other, but simulating head-on collisions allows us to probe the extreme physics of these merger events. The physics we test are hybrid stars and phase transitions of neutron star matter, as the most extreme manifestation of matter in the observable universe neutron stars need to be both descriptors of nuclear matter and of quarks when densities begin to exceed those sustainable by nuclear forces. An investigation of stable conditions for hybrid stars containing these phase of matter conditions is available in [**?**]

References

[1] A. Torres-Rivas, K. Chatziioannou, A. Bauswein, and J. A. Clark, “Observing the post-merger signal of gw170817-like events with improved gravitational-wave detectors,” *Physical Review D*, vol. 99, no. 4, p. 044014, 2019.

[2] B. P. Abbott *et al.*, “Multi-messenger observations of a binary neutron star merger,” 2017.

[3] A. Dhani, D. Radice, J. Schütte-Engel, S. Gardner, B. Sathyaprakash, D. Logoteta, A. Perego, and R. Kashyap, “Prospects for direct detection of black hole formation in neutron star mergers with next-generation gravitational-wave detectors,” 2023.

[4] Vol. 107, no. 12, jun 2023. [Online]. Available: